# DEVELOPING RF-PHOTONICS COMPONENTS FOR THE ARMY'S FUTURE COMBAT SYSTEMS

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## ABSTRACT

The U.S. Army's Future Combat Systems are designed to support the future force with three integrated transformation phases: Concept and Technology Development, Systems Design, Demonstration and Production. The Concept and Technology Developments phase is creating new challenges and opportunities for radio frequency and microwave applications in global positioning, navigation, timing, communications, improved radar target detection, and new forms of combat identification.

The merging of photonics and microwave electronics may revolutionize the traditional microwave technologies and explore many new technology fields. This merging has led to several significant developments such as higher frequency of operation and the capability to change frequency faster with greater agility, the ability to use larger bandwidths at higher frequencies, to improve the stability low phase noise oscillators (useful for low Doppler Radar target detection) and for novel methods of phase array antenna steering. In this paper we review two important system milestones by merging optoelectronics with microwaves, the injection locked dual opto-electronic-oscillator (OEO) and the optical controlled microwave phased array antenna.

## 1. INTRODUCTION

**Why merge photonics with microwaves?** First, RF-Photonic systems can naturally provide very large bandwidth and frequency agility due to the fact that the RF-microwave frequency is many orders of magnitude smaller than the optical carrier frequency. Secondly, optical components, especially, waveguide cables such as optical fibers are order of magnitude smaller and lighter than the traditional microwave components/cables. They have also the advantage of low loss, and EMI immunity. Thirdly, many analog signal processing can be done easily with simplification in optical domain without the slow, complicated digital electronic signal processing system. Finally, the quality factor, Qs of current microwave resonators are in the 1,000-100,000 range. This is the ratio of stored energy to lost energy in a cycle. At optical frequencies it is possible to obtain Qs in the billions, because of the reduced wavelength of light and the very low loss fibers produced today. A 1Km optical fiber coil has orders of magnitude greater Q than the best microwave resonators. In the fiber case the unloaded Q is given by the ratio of its physical length divided by the wavelength of light. If this type of resonator were used in an optical oscillator, it would greatly improve oscillator performance by reducing its close carrier phase noise. Signal to phase noise ratio in an RF oscillator follows the one over Q to the fourth power law (i.e piezoelectric resonators). Presently there are no known materials that can lead to microwave resonators with the performance of optical resonators. By modulating optical carriers at microwave frequencies it is possible to extract the microwave frequencies components, and to use the high spectral purity sources in a multitude of system applications requiring state of the art oscillators and clocks.

Therefore, if we can design the RF-Photonics in smart ways, fully utilize the advantages of the optical systems, and simplify the systems' architecture, we can envision a revolutionized future multifunction RF-photonic system. This system can have all the Radar frond end signal processing such as beamforming, signal generation and synthesizing, filtering and distribution, analog processing, etc done in the optical domain with faster and better performance, light weight, smaller size.

Optical systems have recently reached a new level of maturity thanks to the commercial development of optical telecommunications, resulting in low cost high, quality components. This is an excellent opportunity to merge optical and microwave functions when it is beneficial to improve system's performance.

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This paper discusses the design and development of two novel photonic-microwave projects: one based on space age technology developed at Jet Propulsion Laboratory that can be adapted to Army RADAR applications, involving an injection locked opto-electronic oscillator (OEO), and the other involving a phased-array antenna with a drastically simplified optical true-time-delay array generator.

## 2. INJECTION LOCKED DUAL OEO

In 1996, an opto-electronic oscillator (OEO) was produced at JPL by Yao and Maleki [1,2] which used a long optical fiber as a delay line in a feedback loop of optical and electronic paths as shown in figure 1. The basic concept is to convert

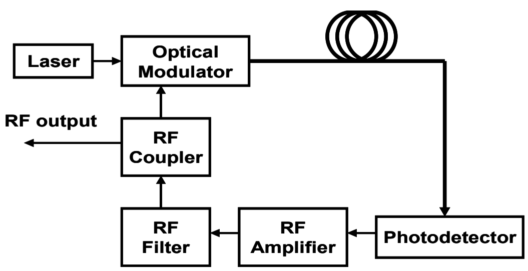


**Figure 1 Block diagram of Opto-Electronic Oscillator**

microwave oscillations into modulated laser light and send it in a long wound optical fiber. At the other end of the fiber a photodetector converts the modulated light signal back into microwave signals which are amplified and filtered by a microwave filter, which in turn is fed into the optical modulator, closing the feedback loop. Several kilometers of low loss optical fiber in the OEO loop can generate a cavity with Q values higher than $10^9$, which is several orders of magnitude higher than that from the best commercial microwave filters. In the OEO, the mode spacing is inversely proportional to the resonator delay, therefore, the RF filter is not able to filter out many of the unwanted modes, especially those close to the carrier (<1 MHz).

### 2.1. Injection Locked Dual OEO

To solve the problem of maintaining the high Q of the multi-loop system and eliminating any spurious modes, we propose a new injection locked, dual OEO scheme. Injection locking schemes have been used and studied previously in non-optical RF oscillators [3, 4], and demonstrate a reduction in phase noise in oscillators. As shown in Fig. 2, the RF output signal from a high-Q long-fiber single-loop master OEO is injected into a short fiber slave OEO and lock the oscillation frequency and its phase. The length of the slave OEO's optical fiber is chosen such that only one mode is allowed to pass within the RF-filter bandwidth. The master OEO's long fiber produces the necessary high Q and the slave short loop OEO filter out the spurs.

We built a master OEO using slightly more than 6 km of Corning SMF28 optical fiber, having an effective index of refraction n of ~1.46 at 1550 nm, which is the wavelength of the single-mode laser. The frequency spacing of the modes is $\Delta f \sim c/nL$, where c is the speed of light and L is the fiber length. The $\Delta f$ in the master oscillator is about 34 kHz. The RF-filter used in the master OEO has a center frequency at 10GHz and a filter bandwidth of 8 MHz allowing hundreds of modes to oscillate. Figure 3a shows the spectrum of the master OEO measured. The envelope of the multi-modes reflects the pass-band characteristic of the RF-filter. Figure 3b shows the single peak spectrum of the slave OEO (composed of a short ~50 m optical

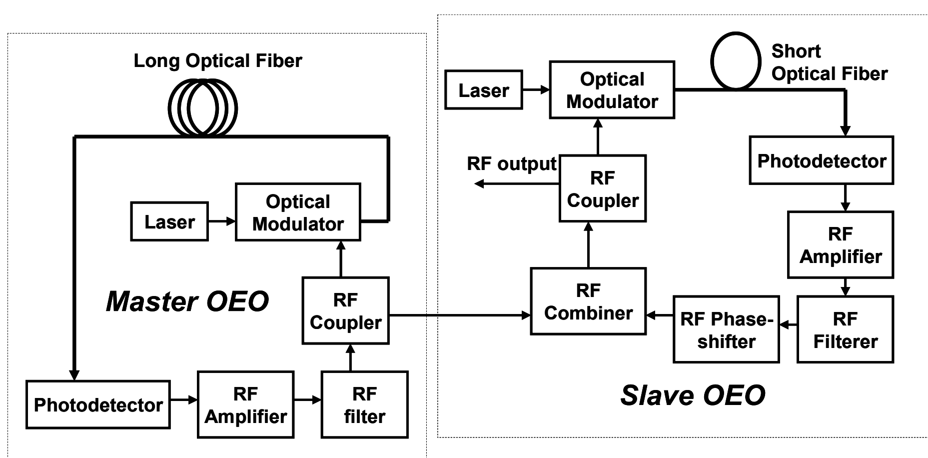


**Figure 2. The block diagram of our injection-locked OEO.**

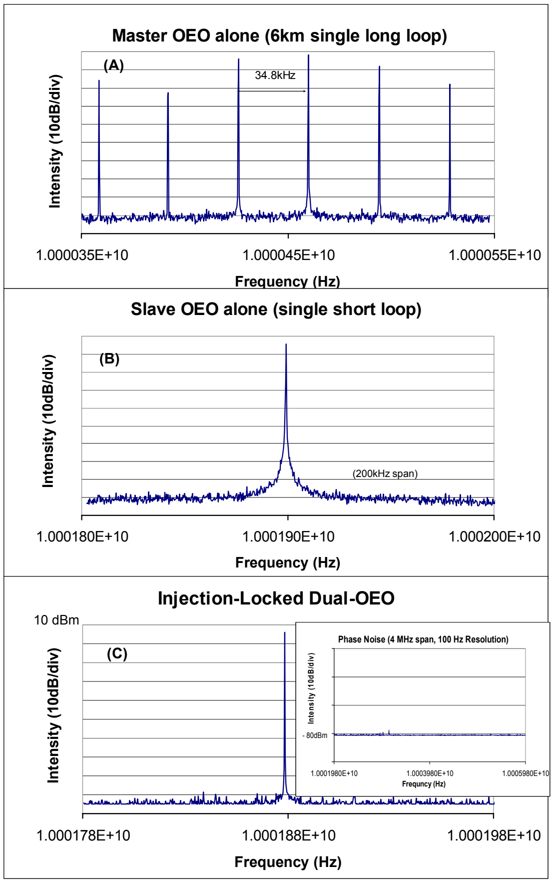


**Figure 3 Experimental data for the oscillator output. (A) Master OEO, (B) Slave OEO and (C) Dual OEO.**

fiber length). The multi-mode signals of the master OEO are injected into the slave OEO. An RF phase shifter is used to bring the slave OEO's oscillation into the locking range with one of the strongest modes of the master OEO. When locked, the side modes are drastically reduced. Fine tuning of the slave loop phase makes the multi-mode spurs disappear from the measured RF spectrum as shown in Fig 3c.

## 2.2. Phase Noise Measurement

In figure 4 we show the preliminary measured phase noise data. There are a few peaks expressed by dashed lines which are associated with the 60 Hz AC power sources.on all the voltage supplies of our OEO. We verified from the raw data that the frequencies of these peaks are exact multiples of 60 Hz. We could eliminate those peaks from the noise spectrum by replacing 60 Hz AC switching power supplies by batteries. We know that if we have any spurs, they must be located at 34.8kHz and 69.6kHz in our phase noise spectrum. We can see some small peaks that may be associated with the spurs, but their intensity level is well below -140dBc/Hz which is much lower than the spur level reported from the previous OEO work. The preliminary noise data also indicates a low phase noise level below -110dBc/Hz at the low offset frequency range of 10-100Hz. However, the frequency tuning of our reference oscillator is somewhat difficult due to the poor design of the tuning mechanism. This makes phase-locking difficult using low gain phase-lock loop. Therefore, there is possible noise compression at the low

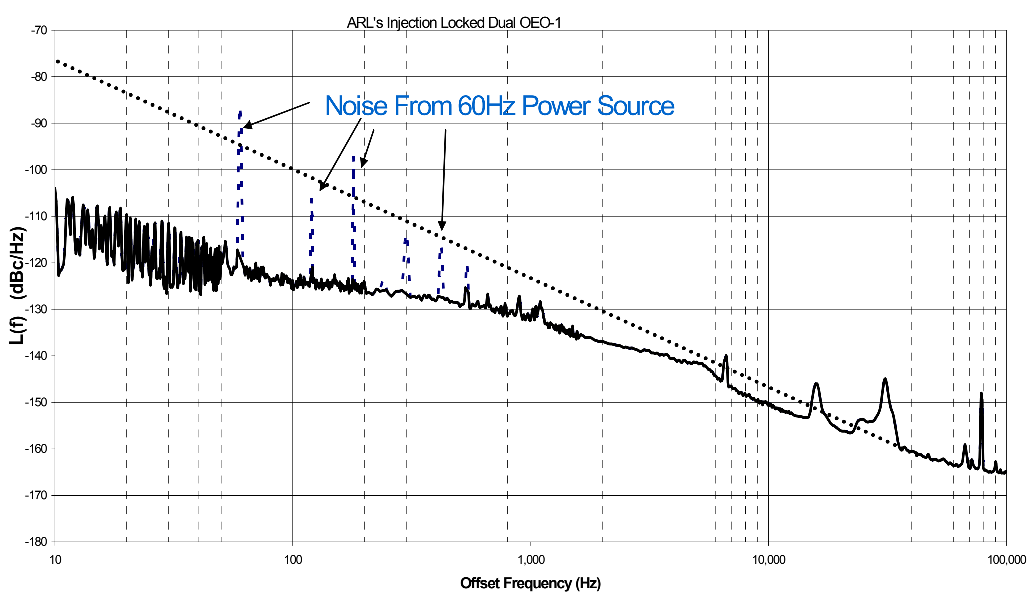


**Figure 4 Phase noise measurement of injection-locked dual Opto-Electronic Oscillator. 60Hz noise from power supply is graphed with dashed line.**

offset frequency range due to the relative high gain of the phase-lock loop and data below a few hundred Hz was outside the measurement calibration. To be safe in the interpretation of the data, we have drawn a straight dotted line as upper range in the noise spectrum, under which we believe, the real noise level should be. The injection-locked OEO was laid out on an optical table during the measurement in an environmentally controlled laboratory, with minimum thermal instability.

## 3. RF-PHOTONIC PHASED ARRAY ANTENNA

Microwave-photonic, phased-array, antenna technologies offer new opportunities for designing arrays with thousands of elements and handling the bandwidth requirements of multifunctional antennas. Photonic technologies provide an interconnect solution for future ground-based, naval and airborne phased array radar and communication antennas. The array meets stringent requirements for bandwidth, frequency agility, EMI immunity, size, weight and cost. These engineering challenges are difficult or impossible to meet using conventional RF/electronic methods. Therefore this is a highly desirable concept for the Army's Future Force missions.

We proposed a novel microwave-photonic phased-array antenna, based on a simplified optical true-time-delay array generator for microwave beam-forming and steering. The unique architecture of the true-time-delay array generator eliminates the need for optical switches, 1xN splitters, multiple lasers or any Wavelength Division Multiplexing device. Therefore, the cost of such a system can be reduced significantly.

### 3.1. True Time Delay Array generation

There are hundreds of proposed optical true-time-delay generation schemes for the photonic antenna system. For an N-element array with M-bit steering resolution, most of these systems require either 1 laser-transmitter with a 1 x N beam splitter, an N-optical-switch matrix to switch $2^M$ optical time delay lines, or a multi-wavelength system with $2^M$ laser-transmitters, a $2^M$ x 1 combiner, a WDM-switch, $2^M$ optical time delays, and an N-channel WDM switch/distributor. Therefore, for each antenna element, $2^M$ time-delays can be independently provided. However, a system with N=1000 elements and M=10 bits requires millions of devices and can cost millions of dollars.

Most true-time-delay array generator architectures have to generate all the discrete time delays needed between any antenna elements. For each steering angle, the generator has to rout the optical path of each channel with the appropriate delay, increasing the complexity of the system. For steering a phased array antenna, the problem can be simpler than most proposed architectures, since the delay required by the antenna elements is not independent, as shown in figure 5.

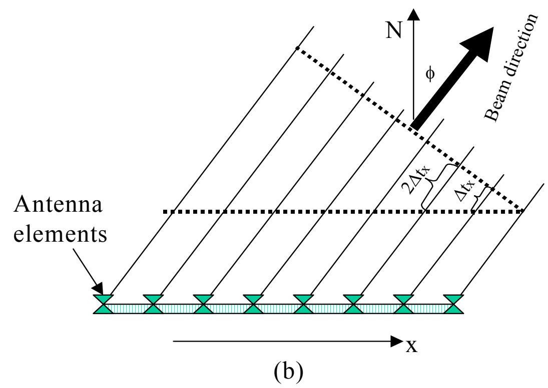


**Figure. 5. Time delays for phased array antenna.**

Only one variable time delay $\Delta T_x$ (or phase delay $\Delta\phi_x$) is created between each consecutive element-row. Correspondingly, only one time delay $\Delta T_y$ (or phase delay $\Delta\phi_y$) is needed between each consecutive element in each column. For a one dimensional N-element array, there is an integer multiplication of the same time delay, giving $\Delta T_{x,}$ $2\Delta T_{x,}$ $3\Delta T_x$ …$N\Delta T_{x.}$; therefore, for one dimension, the problem is reduced to a single variable. Based on this concept, we built a continuous variable time delay unit in free-space optics that is controlled by a linear displacement mechanical drive. This unit can automatically duplicate the time delay by N times and the N optical outputs with $\Delta T_{x,}$ $2\Delta T_{x,}$ $3\Delta T_x$ …$N\Delta T_{x.}$; delays can be directly tapped.

### 3.2. Photonic Antenna Demonstration

To demonstrate this optical true-time-delay generator scheme, we built a 16-element true-time-delay array generator with a simple optical path duplication architecture, which uses free-space optics with a linear displacement mechanical drive. This system is a low cost feature. The true-time-delay generator was inserted into a 16-column optically controlled phased-array antenna system having 4 elements per column (i.e., a 4 x 16 array). The elements in each column are simultaneously fed so the array exhibits one-dimensional phased array steering in the azimuthal directions.

Figure 6 is the block diagram of the whole antenna system. The antenna system has a center frequency of 3 GHz. A commercial laser transmitter is used and modulated at 3 GHz. The optical signal is

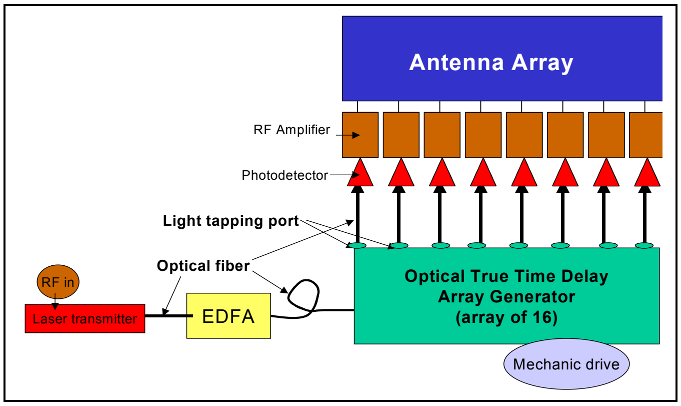


**Figure 6. The block diagram of the photonic phased array antenna test system.**

**Figure 7. The Photonic phased array antenna system in the microwave test chamber.**

amplified by a commercial 17dBm Er-doped fiberoptics amplifier (EDFA). Sixteen output optical signals were sent to photodetectors that fed the antenna elements. Fig. 7 shows the picture of the whole antenna system mounted in a microwave anechoic chamber. The material cost of the whole antenna system (excluding labor) is under $20K. The antenna patterns are reported in figure 8, for $0^o$ (top), $-13^o$ steering (center) and $30^o$ steering (bottom). To reduce the side lobes, we built a 16x4 elements antenna system with a Dolph-

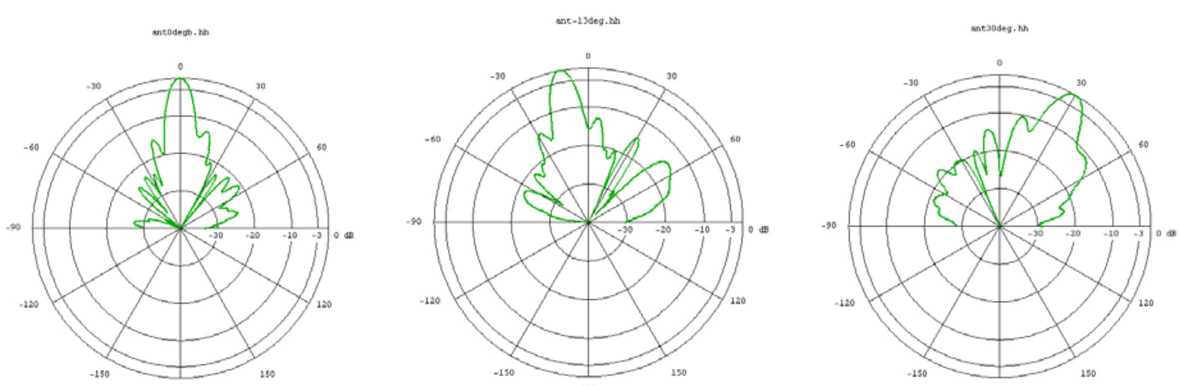

**Figure 8. Antenna beam patterns for $0^0$, $-13^0$, and $30^0$ steering from the preliminary test of the opto-electronic phased array antenna.**

Tschebyscheff array power distribution in the optical domain and converted to microwave power. This showed some improvement for side lobes reduction over a system without the Dolph-Tschebyscheff distribution. Phase and amplitude controls for the array beamforming have been achieved. Beam steering from 0 to +/- 45 degrees in the azimuthal direction has been demonstrated

### 3.3. Design for Transmit/Receive functions

A 3-GHz microwave center frequency was selected because of the low cost and availability of photodetectors in this frequency range, although actual military radar/communication antennas may operate at other microwave frequencies. In principle, using light as the carrier, our true-time-delay array generator can operate at any microwave frequency by frequency translating the high-speed laser/modulator and photodetectors to the appropriate frequency. In fact, higher frequencies are an advantage for our true-time-delay generator, because the physical displacement of the light path is smaller for the same steering angle (i.e., at 3 GHz, ~38mm displacement is required for the steering range, at 30 GHz, only ~3.8mm displacement is required).

We are also designing a transmitting/receiving system so that a single RF-photonic beamforming is used for both transmit and receive functions. Figure 9 shows the diagram of the designed transit/receive conversion system. For transmission, we use the optical true time delay array generator to generate 3GHz microwave for each channel with an appropriate time delay. A switching circuit can switch the system into receive mode, so that optical true time delay array generator can generate an array of local oscillator (LO) signals for the receiver system.

We are working on the next generation optical true time delay phase array antenna system, using one dimensional photonic bandgap waveguide as an optical wavelength dependent time delay generator. This system eliminates the mechanical drive used in the first prototype and also provides opportunity to build multiple RF beams phased array antenna system with no significant additional cost.

## CONCLUSION

We have designed, fabricated and demonstrated a high performance optical electronic oscillator microwave source and an optical true-time-delay array generator for a microwave-photonic phased-array antenna system at an affordable cost. Our future goal is to miniaturize the optical electronic oscillator and the true-time delay generator by using semiconductor optical MEMS technology and photonic bandgap structures so that a large true-time-delay array generator can be built in chip scale. A revolutionary high performance photonic microwave source and an advanced array antenna system can be made using this new technology.


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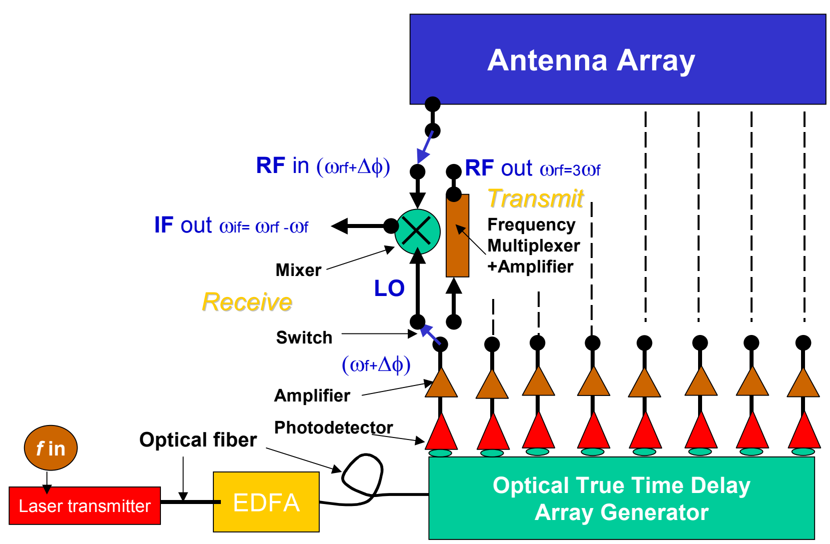


**Figure 9. Photonic phased array antenna with transmit/receive switching system.**

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